Physics Insight from Plasma Shaping of TCV Tokamak Plasmas - focus on Electron Heat Transport

(TCV = Tokamak à Configuration Variable)

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OUTLINE

1. Motivations for plama shaping
2. TCV tokamak facility
3. Confinement and electron heat transport vs. shape
   - 3a. Confinement shape enhancement factor (OH, high collisionality)
   - 3b. Electron heat transport (ECH, low collisionality)
4. Conclusions on heat transport
5. Outlook on innovative divertors / shapes

1. MOTIVATIONS of SHAPE STUDIES

WHY STUDY also SHAPES different from ITER?

- Test and validation of MHD and transport theory
- New: negative triangularity *improves confinement* (in L-mode!)
- Confinement of τ_E, n_e, β, fast ions... scales with plasma current I_p and $I_{p\ max}$ can be increased by plasma cross-section shaping *without increasing the magnetic field*
- Many other parameters depend on plasma shaping
- Reciprocally, active plasma shaping offers a way to control plasma parameters
- What plasma shape, what divertor for a device beyond ITER? to maximize performance, and reduce heat loads

Shaping variables

- elongation κ
- triangularity δ, *including negative (D- and inverse-D-shaped)*
- squareness
- limited / various diverted, innovative geometry
- single plasmas / doublets plasmas ...
- beyond TCV: aspect ratio R/a

TCV: R = 0.88 m, a = 0.25 m, $R/a \sim 3.5$
$B < 1.54$T,
$I_p \leq 1$MA
elongation $0.9 < \kappa < 2.8$
triangularity $-0.7 < \delta < 1$
(reached parameters)

Many parameters, effects, are influenced by plasma shape

Direct influence of shape ...

- MHD stability sawteeth, modes, NTM, disruptions, TAEs, ELMs, ...
- Transport electron heat, momentum (particle...)
- Confinement pressure limits, edge transport barrier, performance

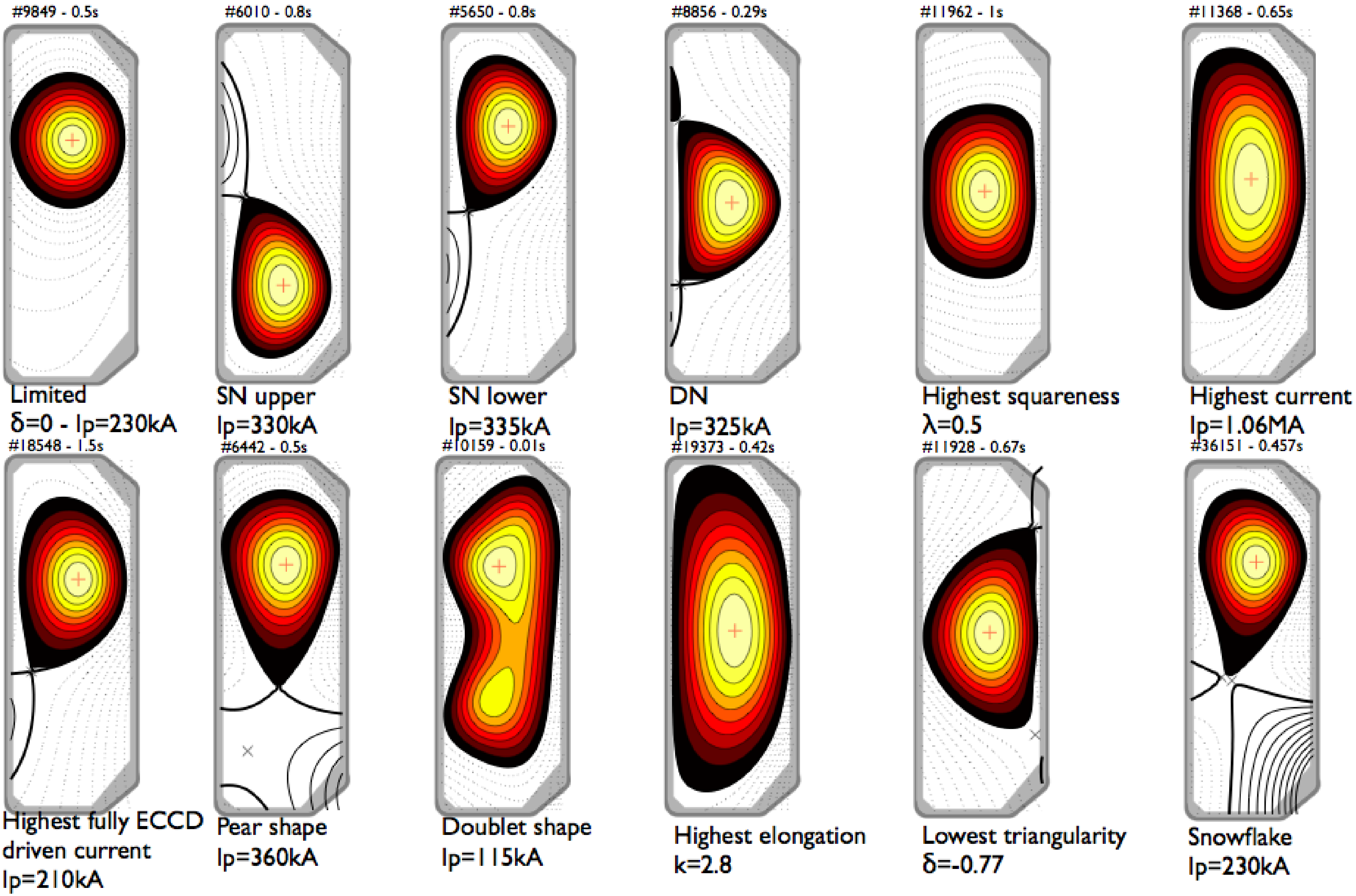
Indirect influence ...

- ELMs(*shape*) [can destroy ITBs (e.g. JET), etc...]
- Sawteeth(*shape*) [can trigger NTMs]

*Dependence on the plasma **confinement regime** ...*

- $\tau_E(\delta)$ *increases towards negative* δ in L-mode (through core transport)
  increases towards positive δ in H-mode (through pedestal height)

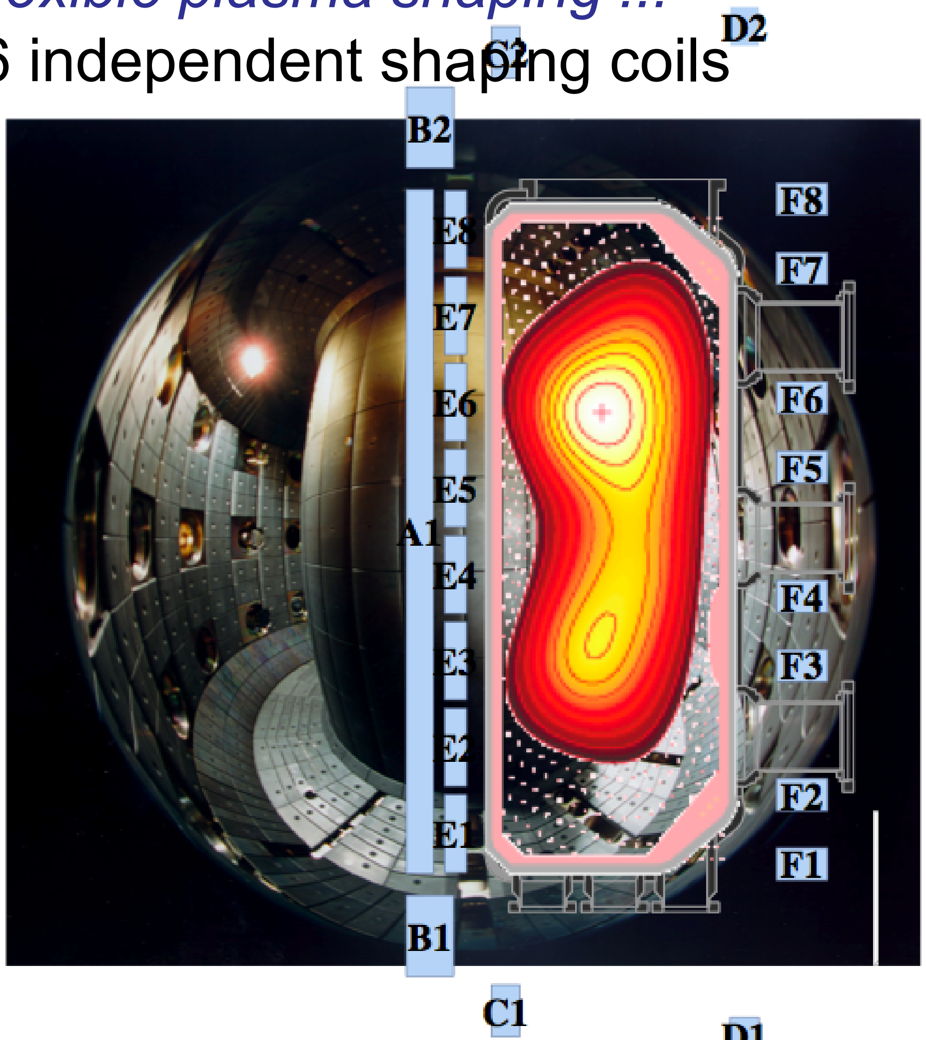
2. TCV FACILITY and SHAPING ACHIEVEMENTS



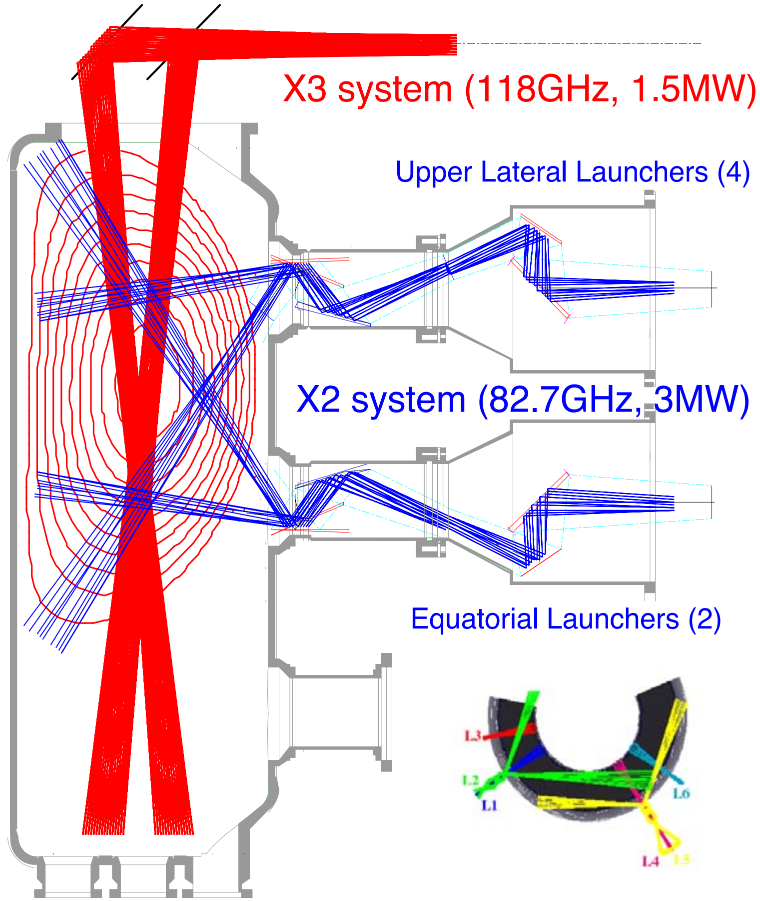
TCV FACILITY

Flexible plasma shaping ...

16 independent shaping coils



... matched by a flexible heating system, entirely based on ECRH



Total: 4.5 MW at 2nd and 3rd harmonic

Cut-off densites: 4.2 and 11.5 10^{19} m^{-3}

3a. CONFINEMENT vs. SHAPE / Ohmic, high collisionality densities ($\nu_{eff} \sim 2.5$-10)

- τ_{Ee} increases strongly with κ
- Mild decrease with δ, in δ>0-range
- Interpretation in terms of a confinement Shape Enhancement Factor (SEF):

$$Q_\alpha = -n_\alpha \chi_\alpha \left\langle |\overrightarrow{\nabla\rho}|^2 \right\rangle \frac{\partial T_\alpha}{\partial \rho}$$

heat diffusivity:
depends on collisions,
shape, etc...

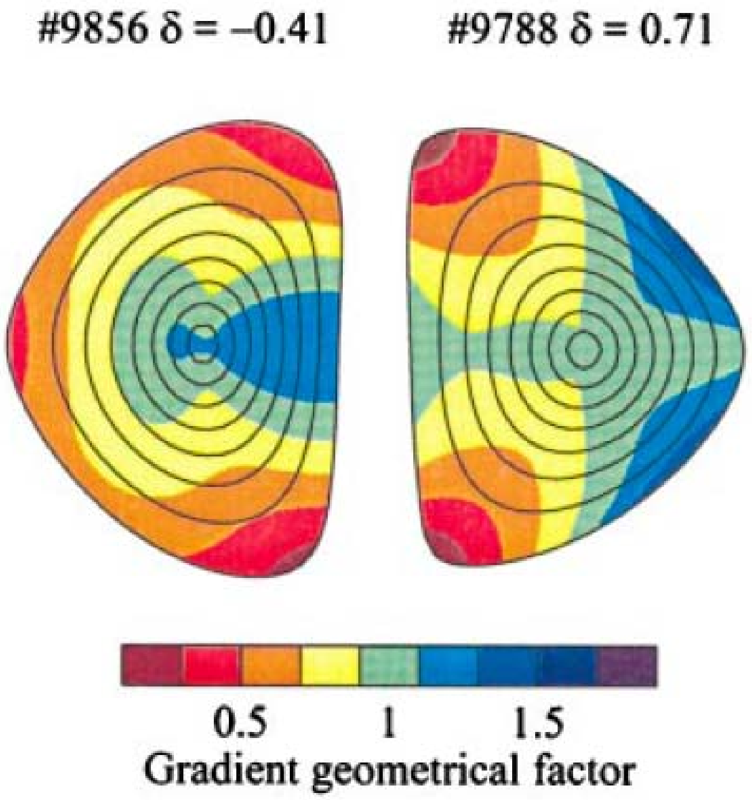
gradient geometrical factor,
expresses flux surfaces sep.,
metric term

Moret PRL97, Weisen NF97

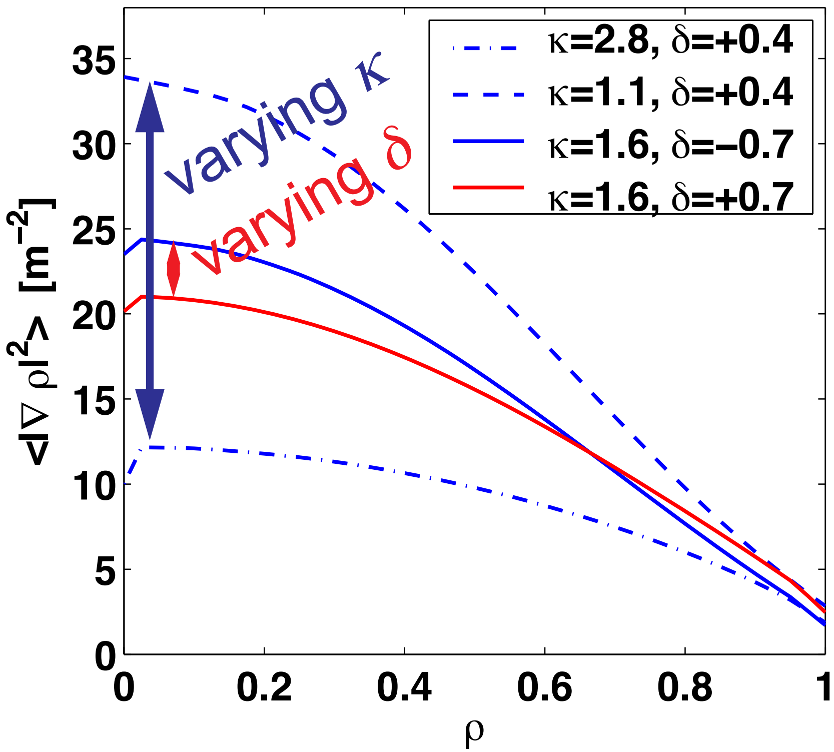
Gradient geometrical factor

gradient geometrical factor

local



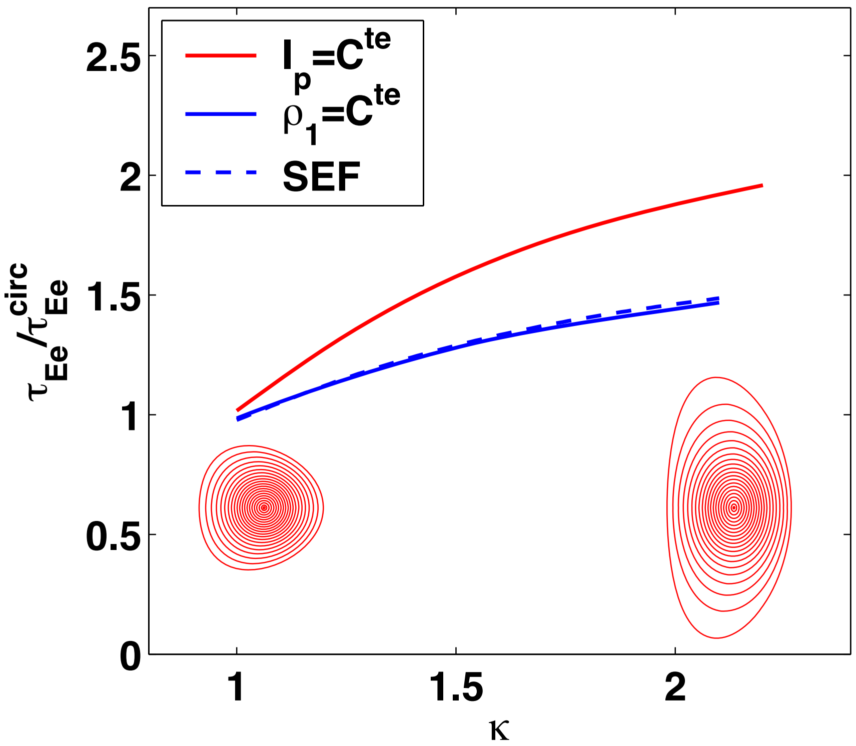
flux surface averaged

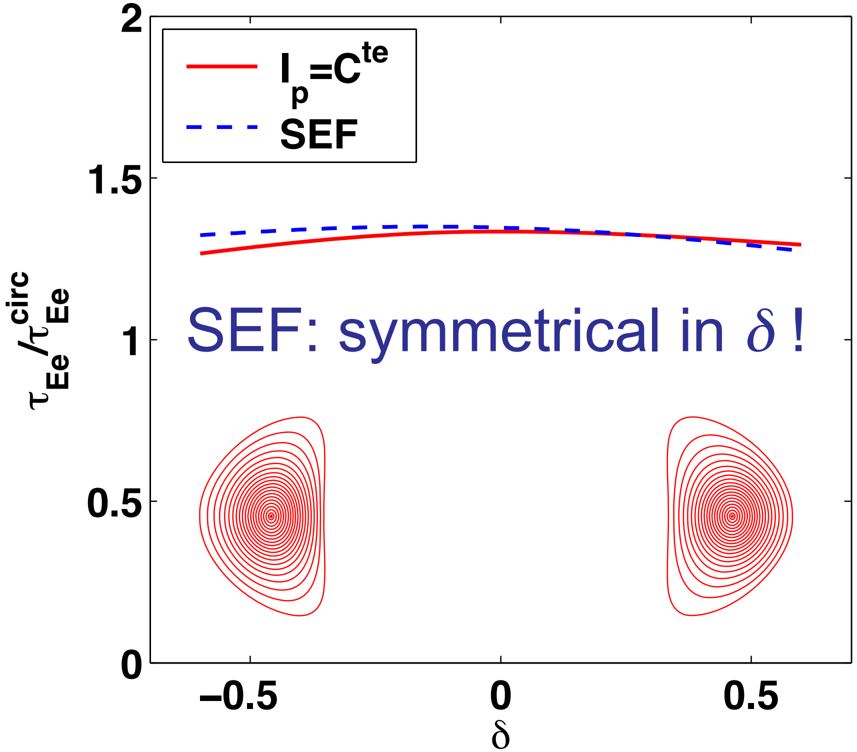


Moret PRL97

SEF: when confinement only due to flux surface separation (χ_e=cst)

$\tau_{Ee\text{ shaped plasma}} / \tau_{Ee\text{ circular plasma}}$ with same χ_e (ASTRA calculations)





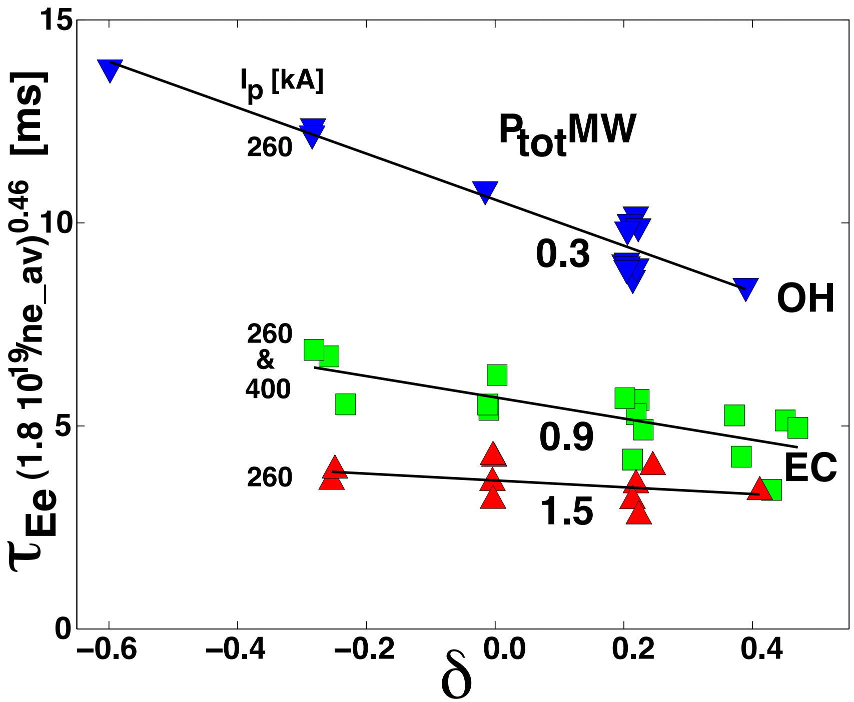
Important to keep sawtooth inv. radius ρ_1~const (self-similar profiles)

SEF found adequate to account for τ_{Ee} variations with shape in OH, at medium densities

Camenen thesis06

ECH confinement at low densities (ν_{eff} ~ 0.2-1)

Central ECH, large δ-range, positive and negative triangularity

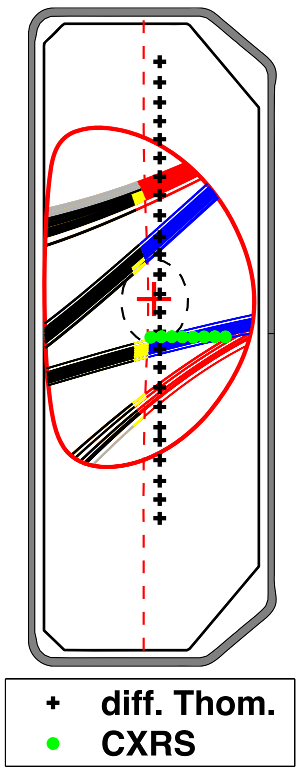


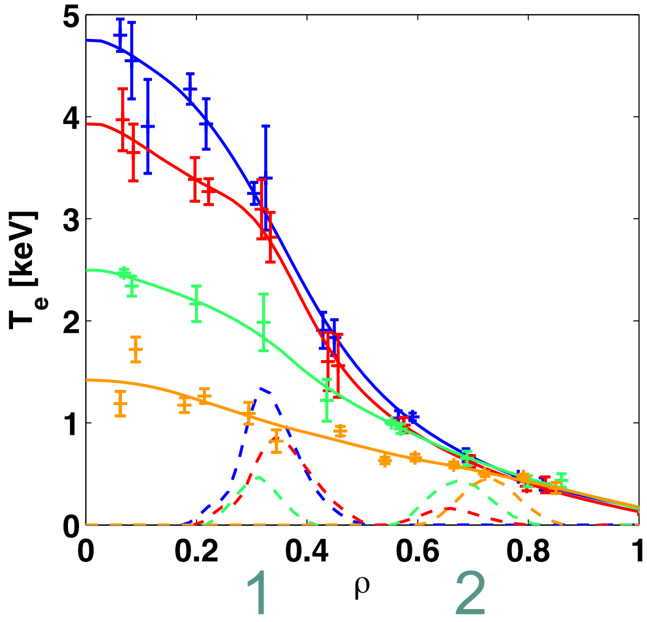
- Strong $\tau_{Ee}(\delta)$ dependence, improvement towards δ<0
- Asymmetry in triangularity not explained by SEF alone: —> *does also χ_e vary with shape?*

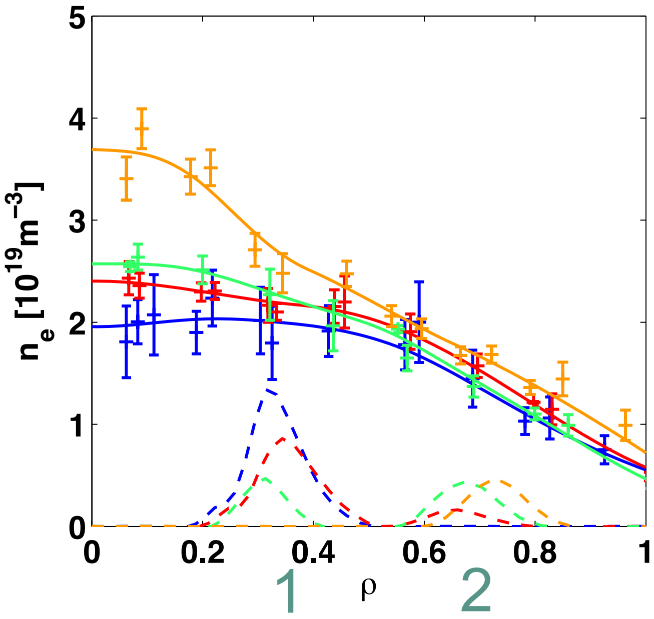
Coda 98, Pochelon NF99, EPS99, Weisen NF98

3b. ELECTRON HEAT TRANSPORT vs shape / EC low n_e (ν_{eff}~0.2-1)

T_e-variation, gradT_e-variation experiments





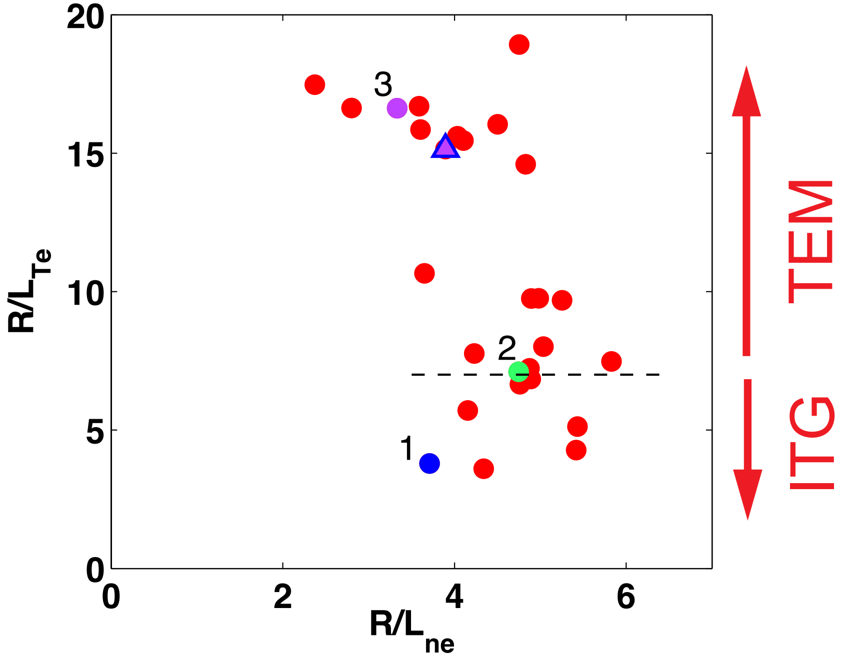


- 2 deposition locations 1 and 2
- Varying $P_{tot} = P_1 + P_2$
  and P_1 / P_2

Camenen PPCF05

Microinstability types in EC plasmas

Type of micro-instabilities (GLF, LORB)



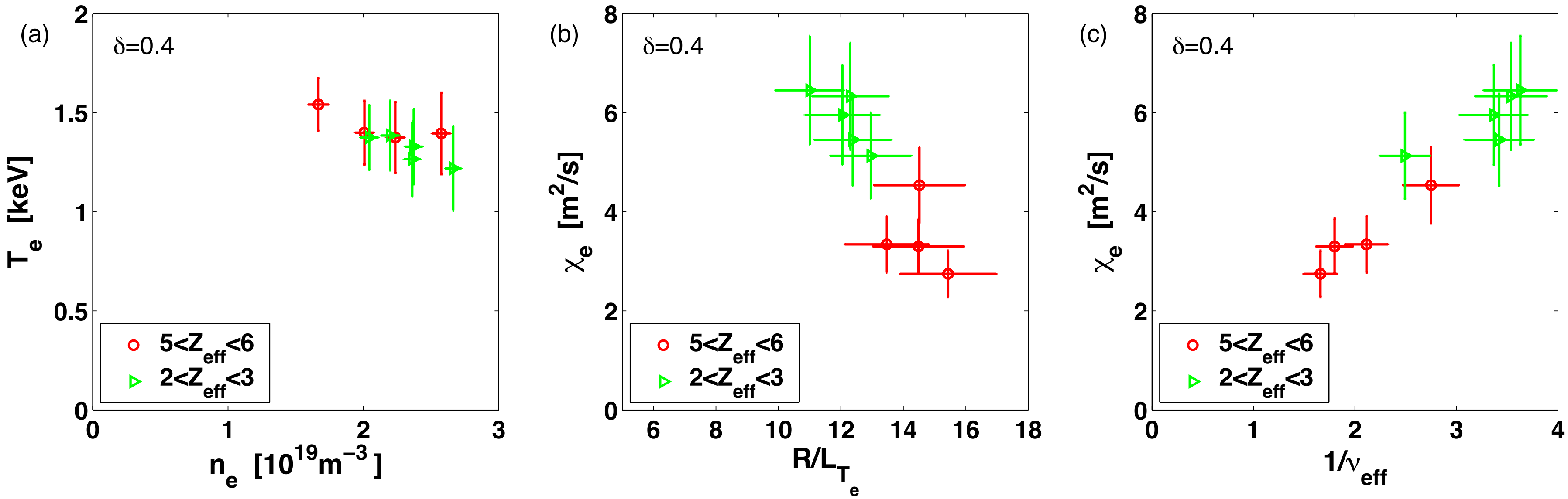
EC plasmas:
High R/L_{Te}>7, in high T_e/T_i,
low collisionality:

TEM dominated regime

(no ETG in 0.2<ρ<0.7 range, due to high Z_{eff} & high T_e/T_i)

Camenen PPCF05, Thesis06

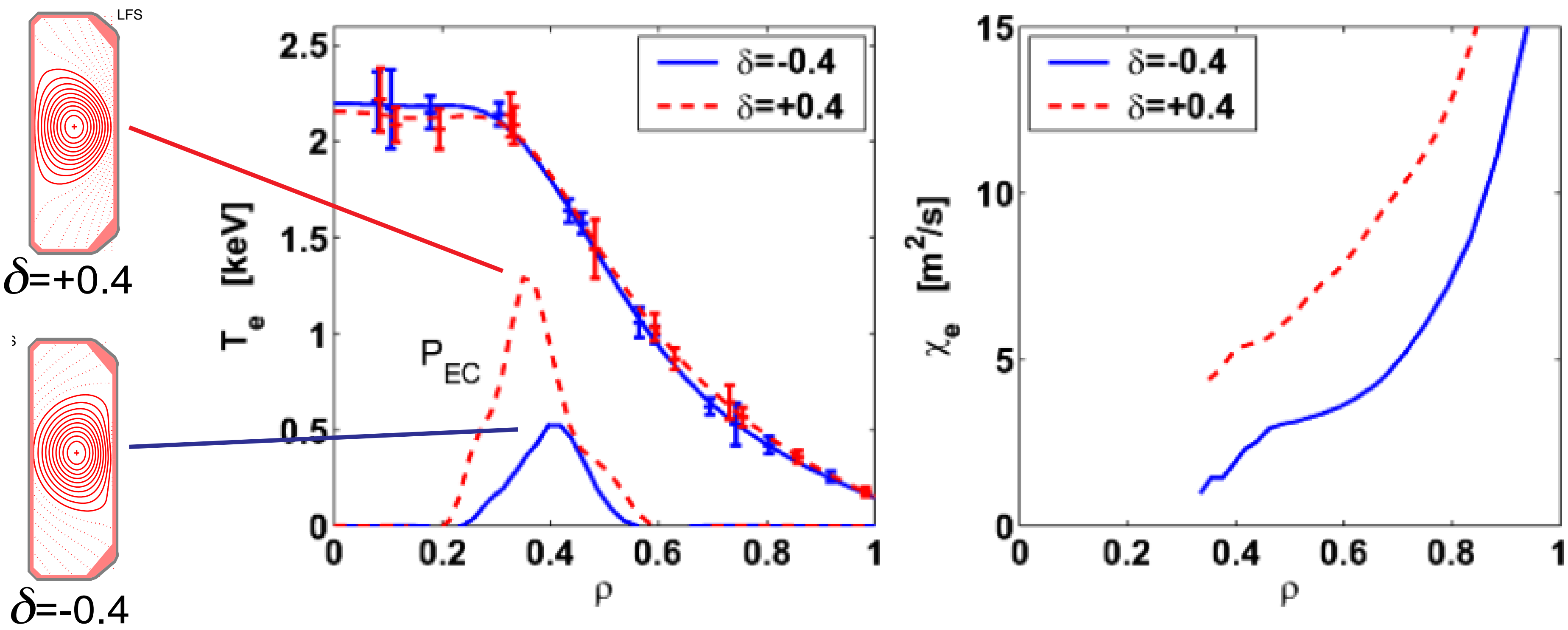
Collisionality effect demonstrated



- The effect of T_e, n_e, Z_{eff} , when combined
  show a clear dependence of χ_e on collisionality ν_{eff}
- $\nu_{eff} = 0.1 R\, n_e\, Z_{eff} / T_e^2$
  $= \nu_{ei}/\omega_{De}$ De: curvature drift
- Diffusivity χ_e reduces with increasing collisionality

Camenen NF07

How to decrease transport by a factor 2 in L-mode ?



1) **change triangularity from positive to negative :**

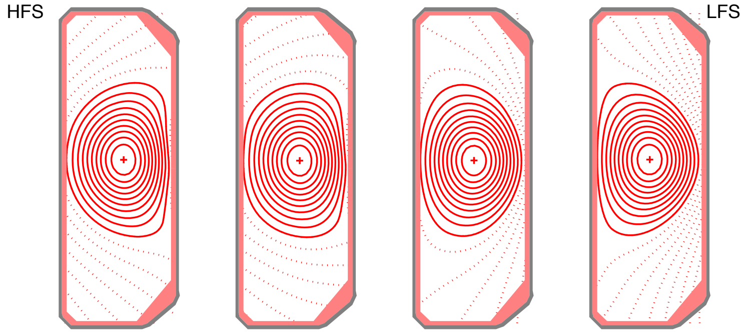
δ = + 0.4 —> - 0.4

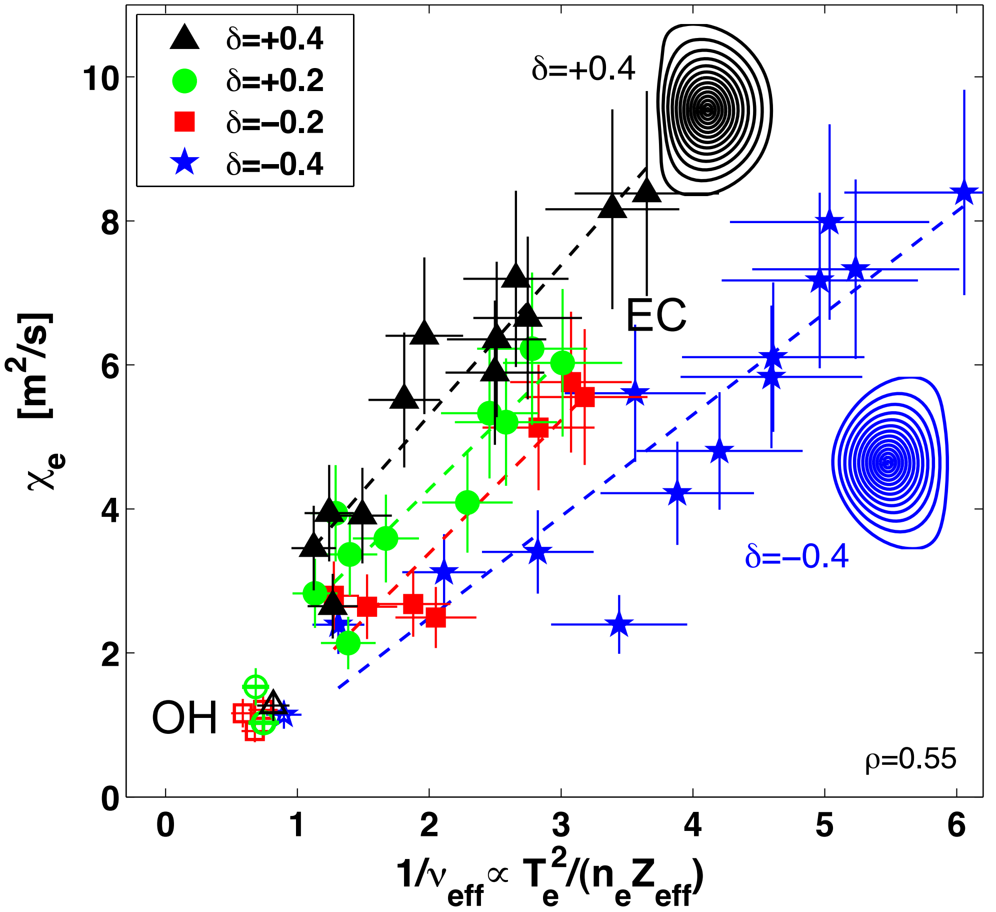
2) **adapt additional power to keep the same T_e, n_e** and q-profiles

—> Result: heat transport is ***halfed*** at mid-radius,
an effect of ***negative triangularity***

Camenen NF07

Shape and collisionality effects separated





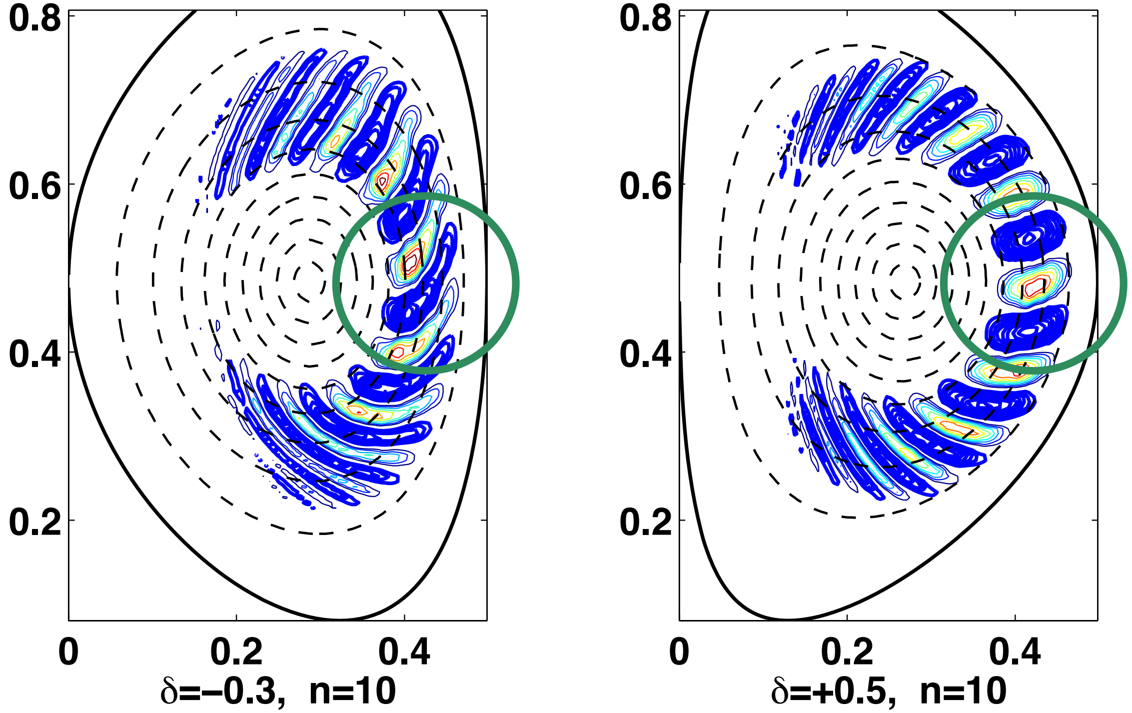
- Collisionality lowers χ_e
- At same ν_{eff}, negative δ reduces χ_e
- At high ν_{eff}, vanishing δ-effect
- Taking account of collisionality ν_{eff} explains the different δ-dependence of OH and EC data

Camenen NF07

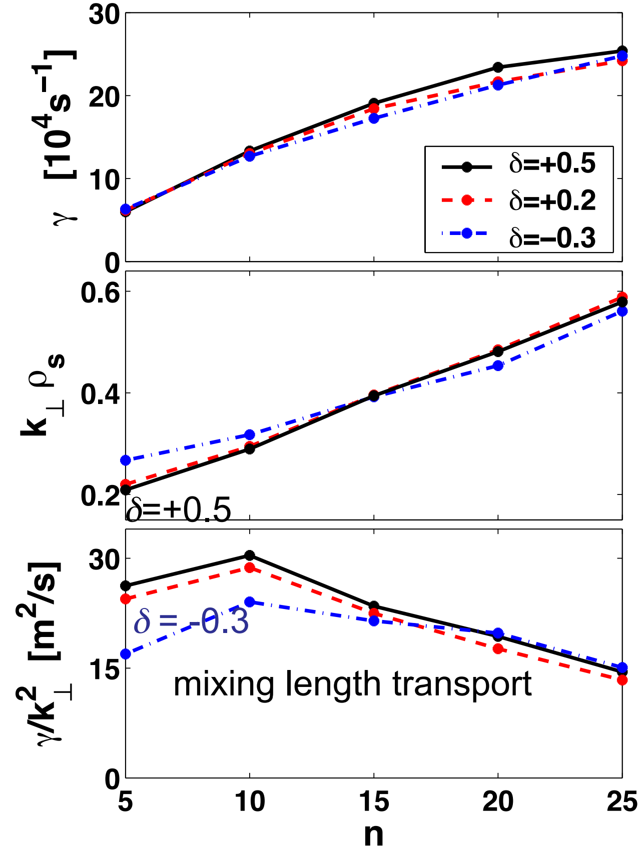
Global TEM micro-instabilities simulations

LORB simulations (gyrokinetic, linear, global, no collisions)

Camenen PPCF05



electrostatic potential fluctuations



Negative δ<0:

-> stronger tilt of eddies at LFS equator!

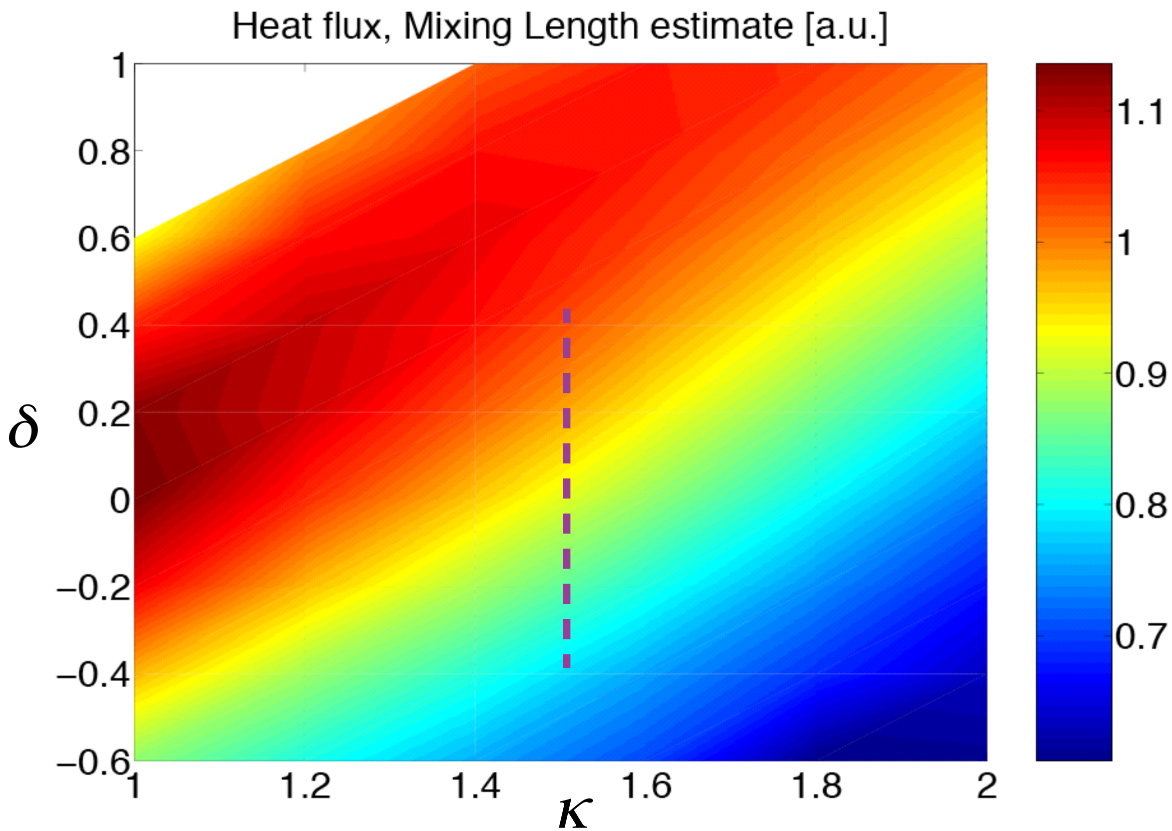
-> *higher* $k_\perp$

-> *lower mixing-length transport*

GS2 linear, local, gyrokinetic calculations

$\chi_{e\ \mathrm{mixing\ length}}$ as a function of (κ,δ)

GS2 (gyrokinetic, linear, local)



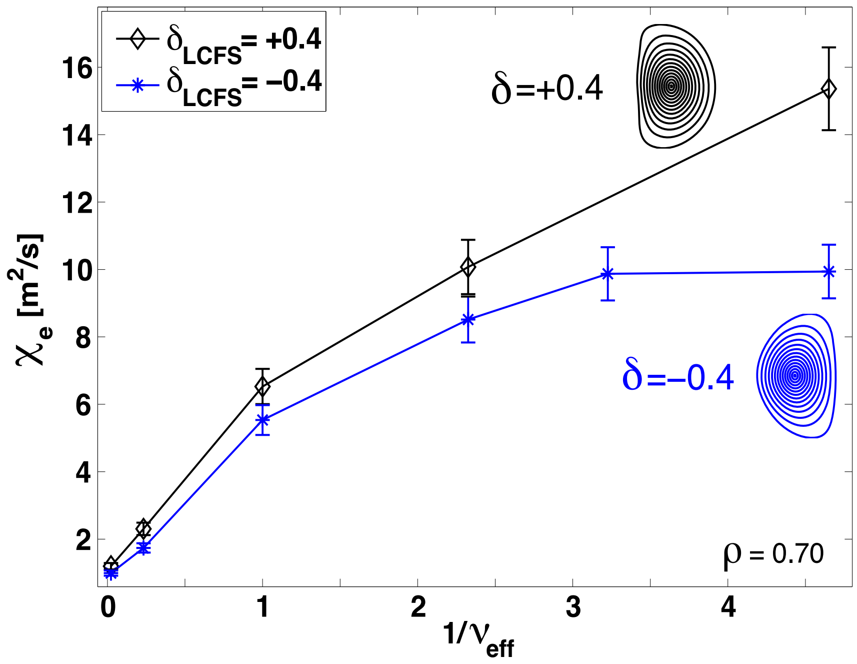
As in above δ–scan expts, χ_{e_GS2} reduces monotonically towards δ<0

Marinoni PPCF 09

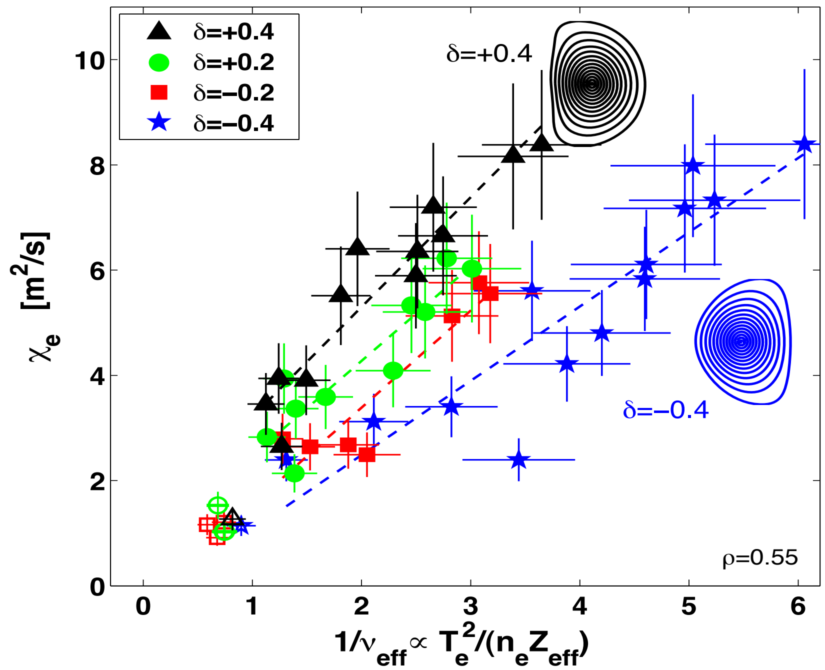
GS2: local, non-linear gyrokinetic calculations, with collisions

effect of shape and collisionality

GS2



TCV



Marinoni PPCF 09

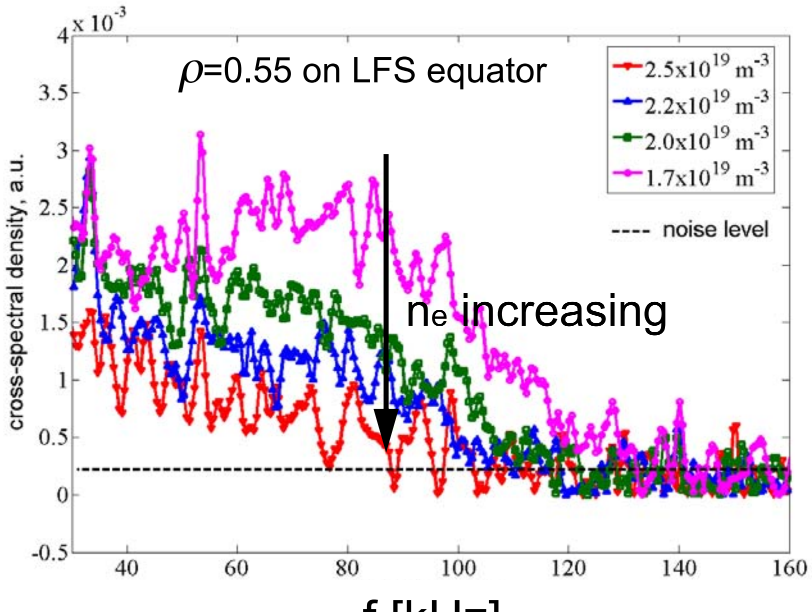
Transport simulations reflect experimental χ_e in TEM regime:

- decrease of χ_e towards high ν_{eff} and negative δ
- triangularity effect on χ_e smaller at high ν_{eff}
- but disagree for the radial dependence: possibly a global effect.

T_e-fluctuations decrease with collisionality (corr-ECE diag.)

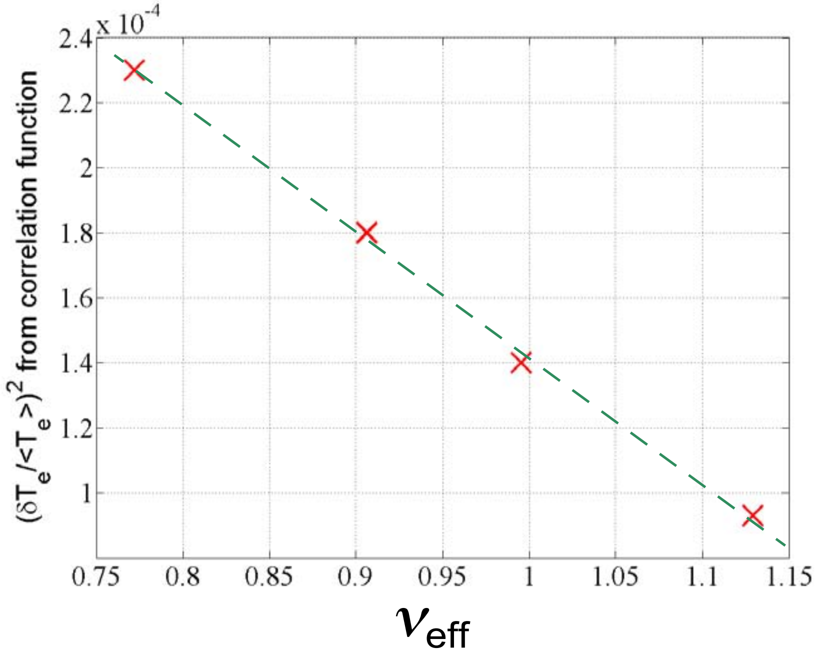
fluctuation spectra decrease with density

Ohmic, q~10, κ~1.4, δ~0.3



fluctuation amplitude $(\delta T_e/<T_e>)^2$

averaged over<30-130kHz>



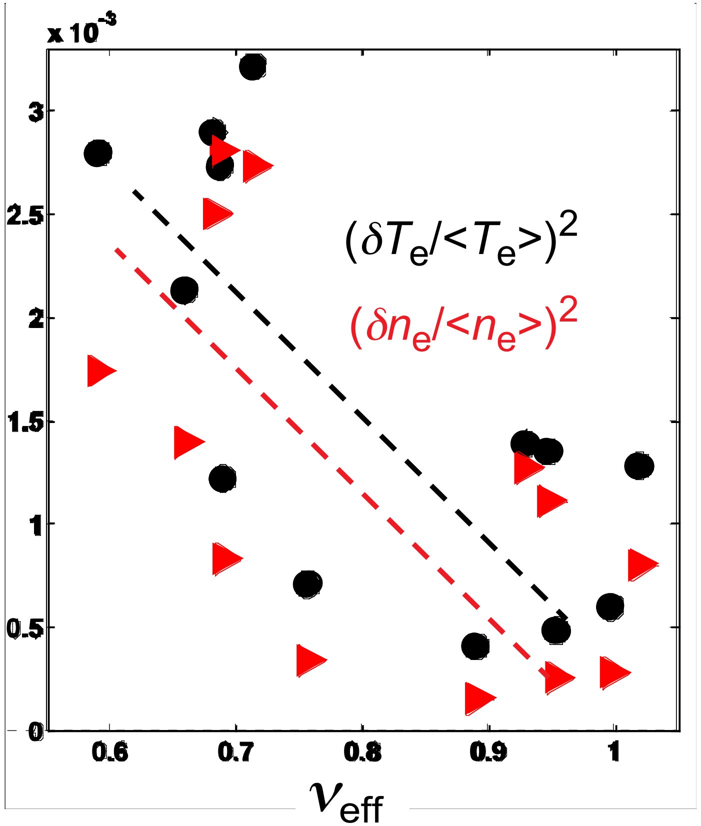
T_e-fluctuations amplitude decrease with collisionality ν_{eff}

Udintsev & Fable US-TTF09

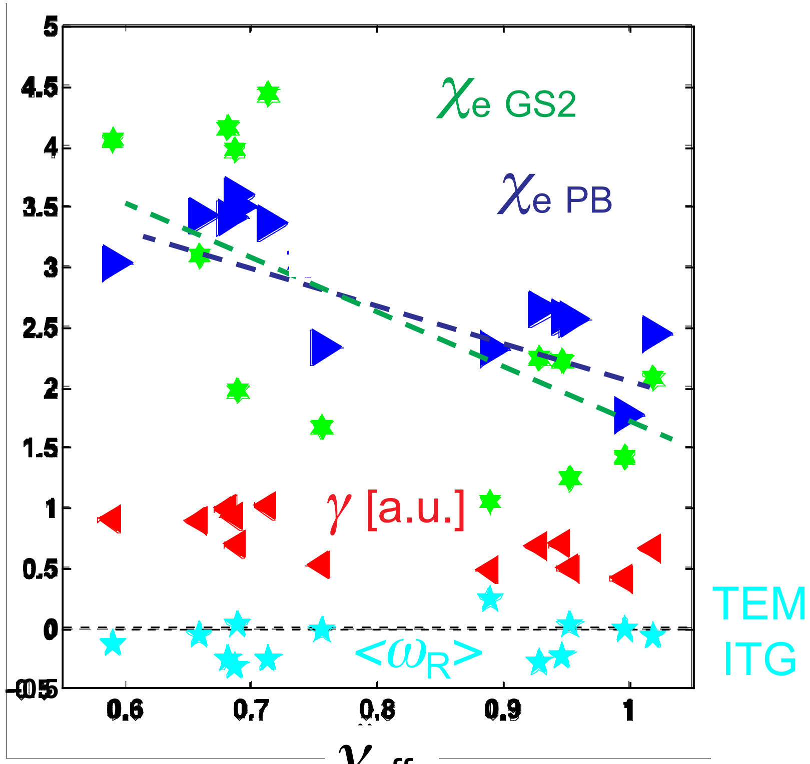
de Meijere: talk **15h** (534, in place of 504)
More on turbulence measurements in TCV

Fluctuation amplitude decrease with ν_{eff}, as predicted by GS2

T_e- & n_e-fluctuations from GS2 decrease with ν_{eff} (as in experiment)



χ_{e_GS2} decreases with ν_{eff}, as χ_{e_PB} from experiment

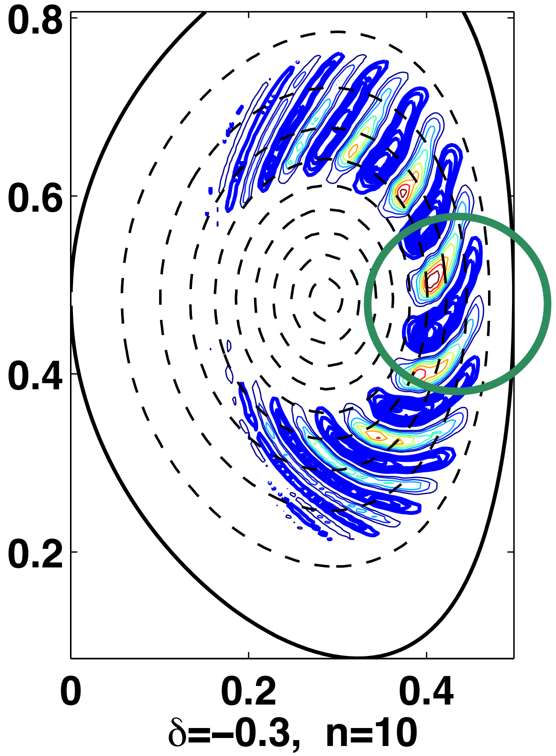


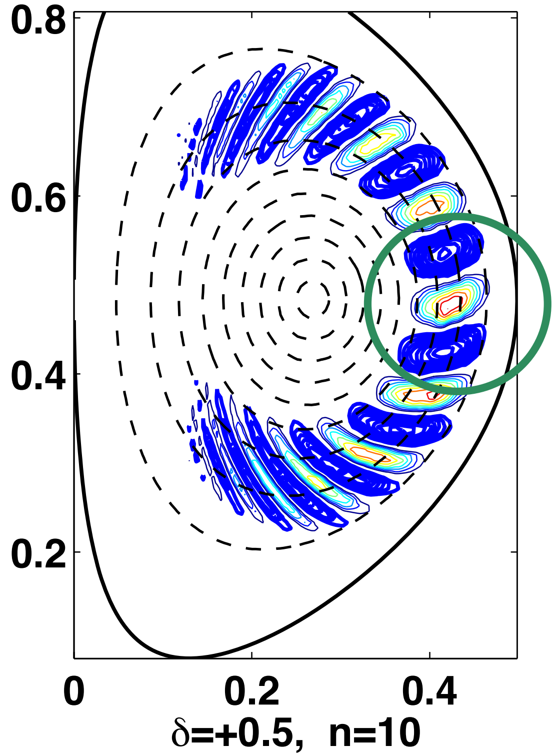
consistent with TEM ampl. reduction with collisions (e^- collisional detrapping)

Udintsev, Fable US-TTF09

Evaluating turbulence correlation length with «corr-ECE diag»

Change of eddy geometry with triangularity
to be measured by correlation-ECE measurements





How close/different are the experimental results
to the linear (or non-linear) global gyrokinetic calculations?

4. CONCLUSIONS on heat transport / shape

- **Role of metric** (flux surface separation)
  SEF, evidenced at high ν_{eff} (where χ_e weakly dependent on shape)
  Confinement improves with elongation

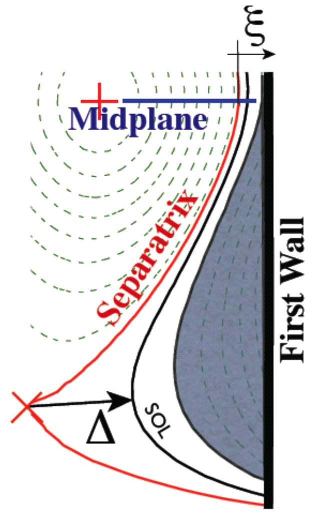
- **Role of collisionality** (χ_e)
  Effect of collisionality evidenced varying triangularity (where SEF~const.)
  At low ν_{eff}, τ_e and χ_e are not found symmetric in δ,
  Confinement improving towards negative δ (in TEM dom. transp.)

- **TEM dominated transport**
  - χ_e decreases with ν_{eff} (electron de-trapping)
  - $\langle \delta T_e / T_e \rangle^2$ decreases with ν_{eff}
  - role of triangularity in (de)tuning resonnance between ω_D and ω_{TEM}
  - global GK calculations show larger $k_\perp$ at δ<0, thus smaller $\chi_{e\_ml} \sim \gamma / k_\perp^2$
    - an effect of magn. curvature & Shafranov shift
    - to be identified at the turb. level (e.g. corr-ECE)

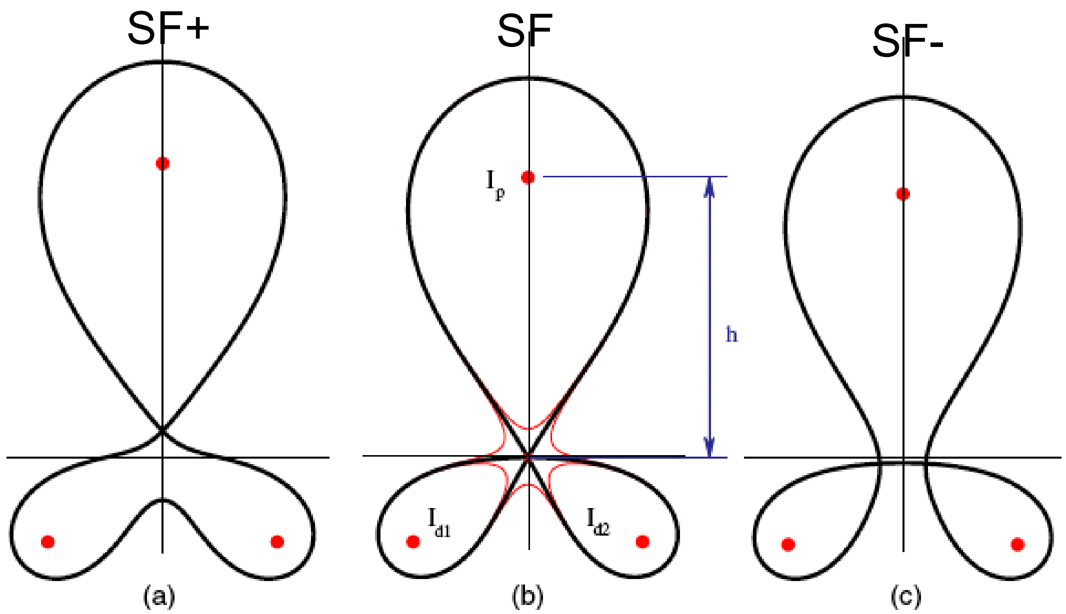
5. OUTLOOK on INNOVATIVE SHAPES: 5.1 Snowflake divertor

On the search of reduction of divertor power heat loads:

- standard quadrupole null —> hexapole null (= SF divertor)



Piras PPCF 09

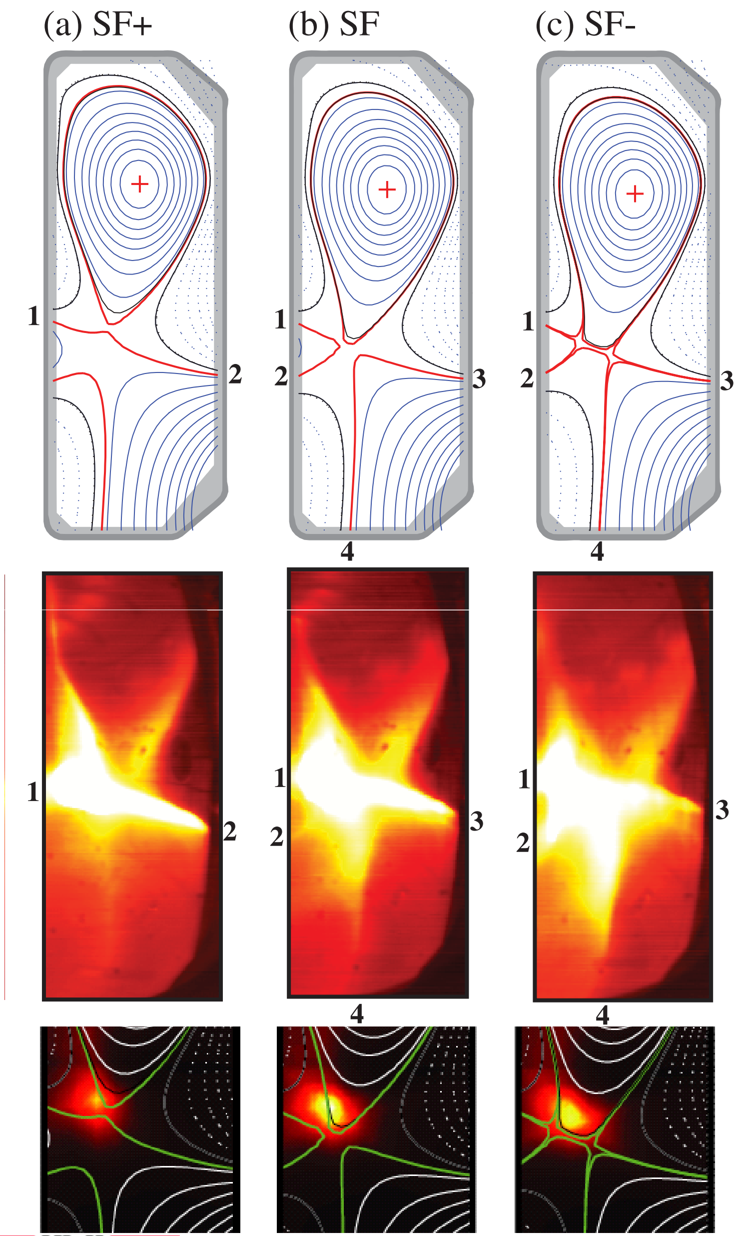


Ryutov PP 07 08

- **larger magn. flux expansion**
  (factor 2-3 over standard X-point)
  —> heat load reduction
- **increased magnetic shear**
  —> improves edge ideal stab., change ELM and H-mode properties?

Pitzschke: next talk 502 on edge ideal-MHD stability

Snowflake divertor concept first tested in TCV



magn. config.

visible light emission

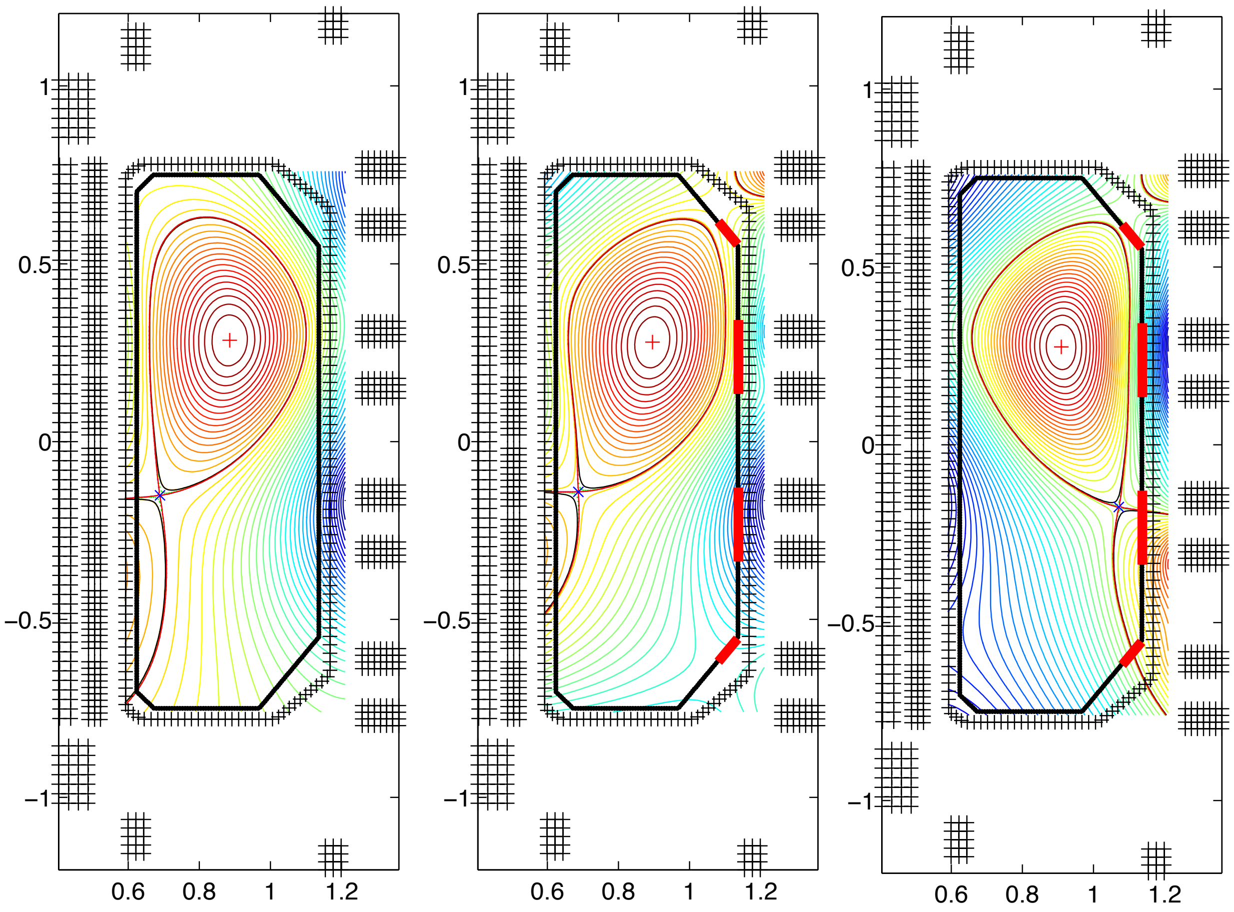
radiated power (AXUV)

Investigation of SF and neighbour configurations (SF+, SF, SF-) :

- distrib. of power on div. legs
- distrib. of power on the walls
- maximisation of radiation power
- H-mode properties ...

Piras PPCF 09

5.2 Towards H-mode at negative triangularity



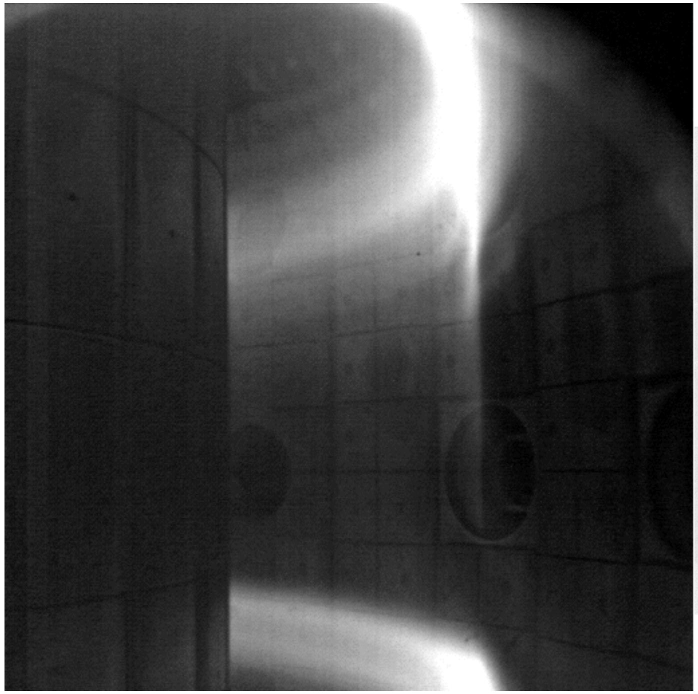
Medvedev EPS09

To learn more about H-mode properties by extending to negative triangularity:

from MHD modeling:
pedestal seems lower
- smaller ELM regimes?
- β-limit & RWM studies at lower power with ECH X3

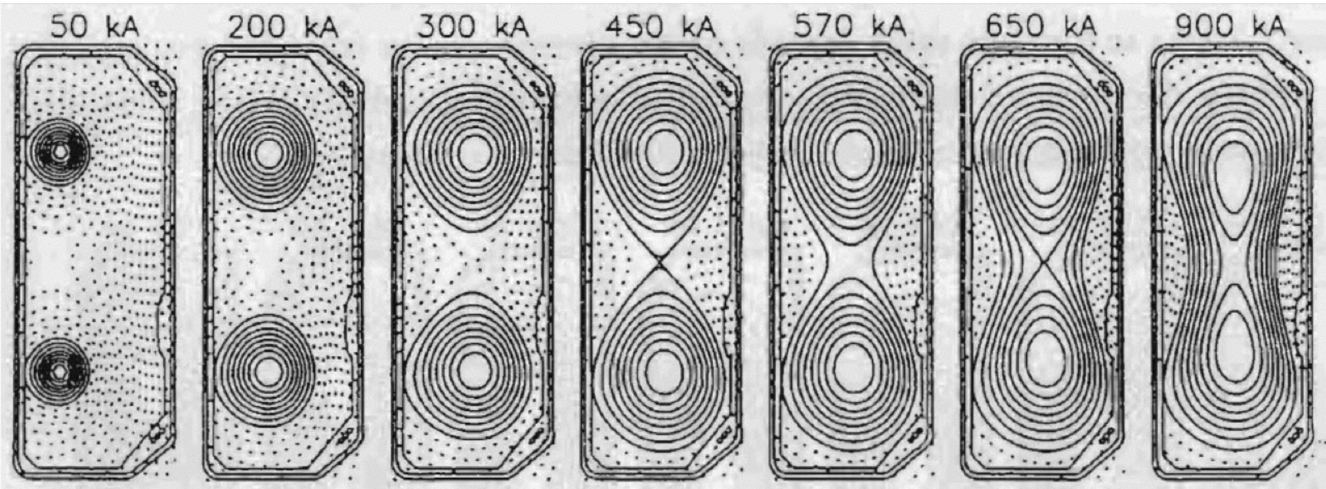
5.3 Doublet configuration: an innovative shape, a divertor concept ?

... on the search of configurations
- with good confinement and enhanced edge radiation properties
- quiescent edge in H-mode scenarios...



double ECH breakdown
using 2 gyrotron beams
(Piras July 2009)

a possible scenario (model calculation)



... under development at TCV

TCV, a flexible, variable shape tokamak
to develop new shapes
to improve models

for concepts improvement
and for ITER

Thank you

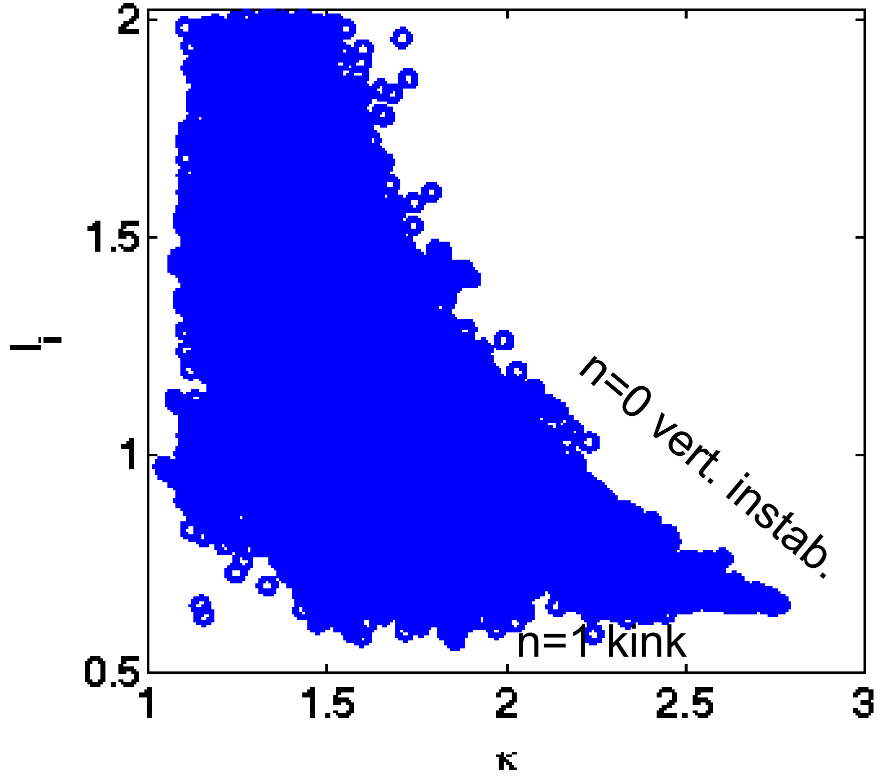
CRPP-Lausanne talks / Plasma Physics Session

- **14h30, 502**
  Pitzschke
  MHD stability calculations for H-mode plasmas
  with Snowflake divertor configuration
- **15h00, 534 (repl. 504)**
  de Meijere
  Measurements of electron density fluctuations in TCV
- **17h00, 508**
  Furno
  Turbulence and transport in TORPEX
- **17h15, 509**
  Federspiel
  Observation of a critical pressure gradient
  for the stabilization of interchange modes in TORPEX

SPARES

Stability limits (Ohmic)

Using high I_N, elongation up to κ=2.8



Operation at high κ limited by

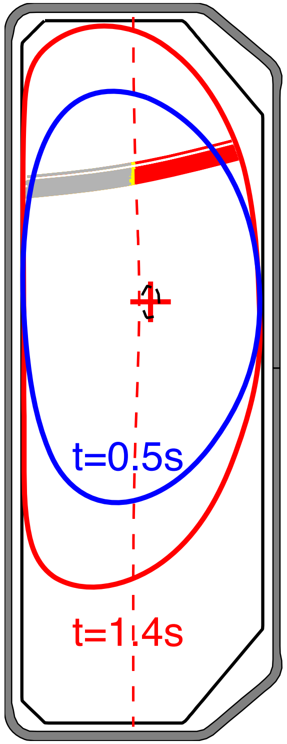
n=0 vertical instability —> broad $j(r)$ required: low-q, high-I_N + fast int. coils

n=1 external kink —> high current limit (I_N & β-limit)

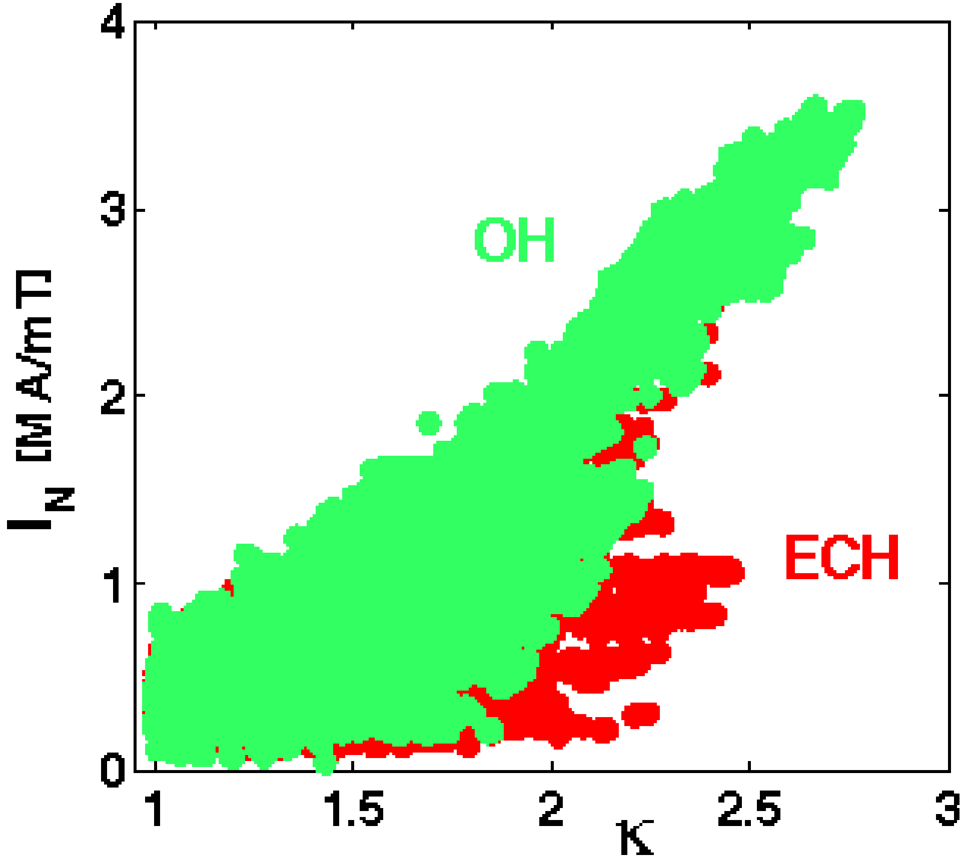
Hofmann PPCF01

High elongation stability limits (off-axis ECH)

At low I_N, vertical stability requires broadening the current profile, done using off-axis ECH, allows reaching κ=2.5 at I_N~1

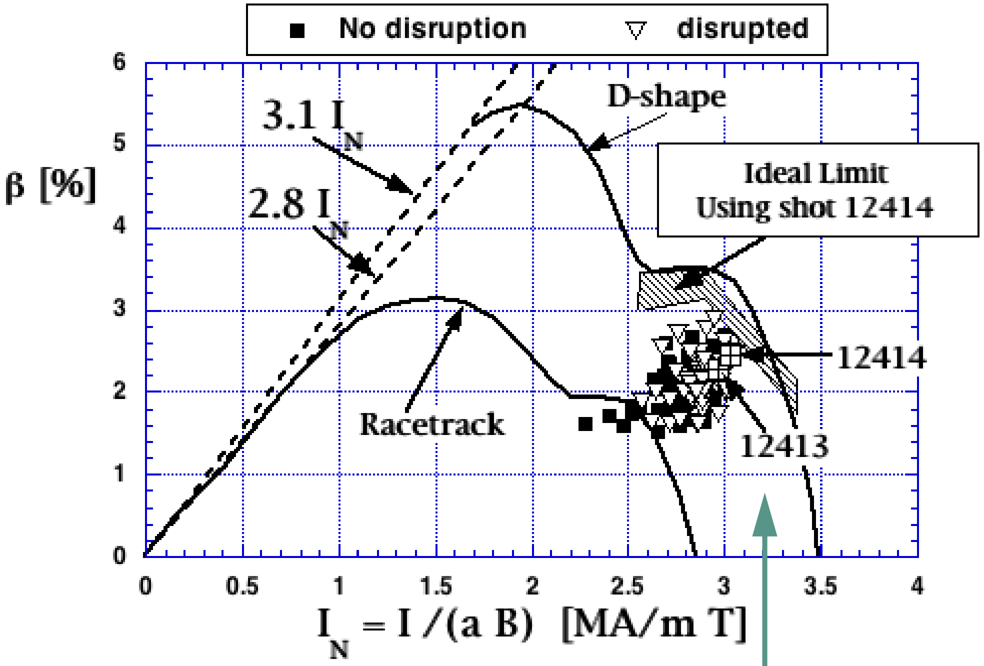


off-axis ECH power
at constant quadrupole field
—> *κ increase*



Pochelon NF01, Camenen NF07, Paley PPCF07

Current limit at high κ



current limit at high κ

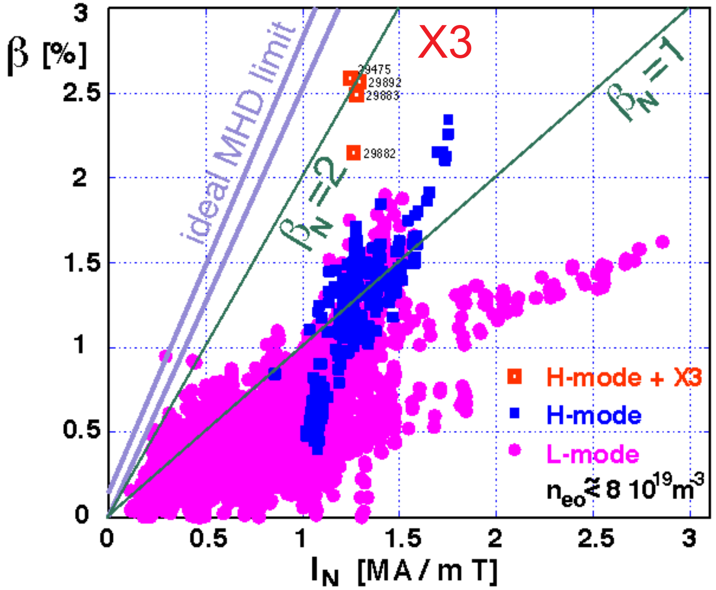
shape influences the β-limit

Ideal MHD predicts correctly the current limit

as often,
resistive modes (m/n = 4/3, 3/2, 2/1)
are found just below the ideal limit

Hofmann PRL97

β-*limit* at high elongation κ ...



β reached at κ~1.6
with1.5MW X3

However, more power is needed
to test the β-limit
in various TCV shapes
—> foreseen to double
the installed X3 power

TCV provides the highest β-values in the
inter-machine spontaneous rotation database
(J.Rice NF07)

Hofmann PPCF01

Porte NF07, Alberti JoPh05, Pochelon SMP05